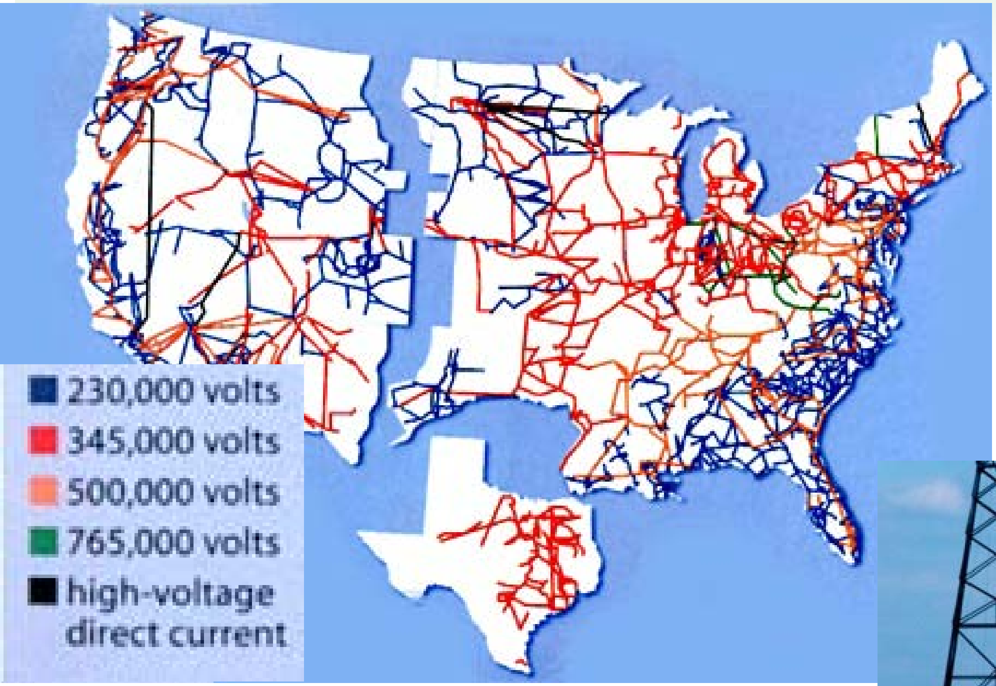
GREEN ELECTRICITY NETWORK INTEGRATION

Monday, February 28, 2011

Electricity Transmission



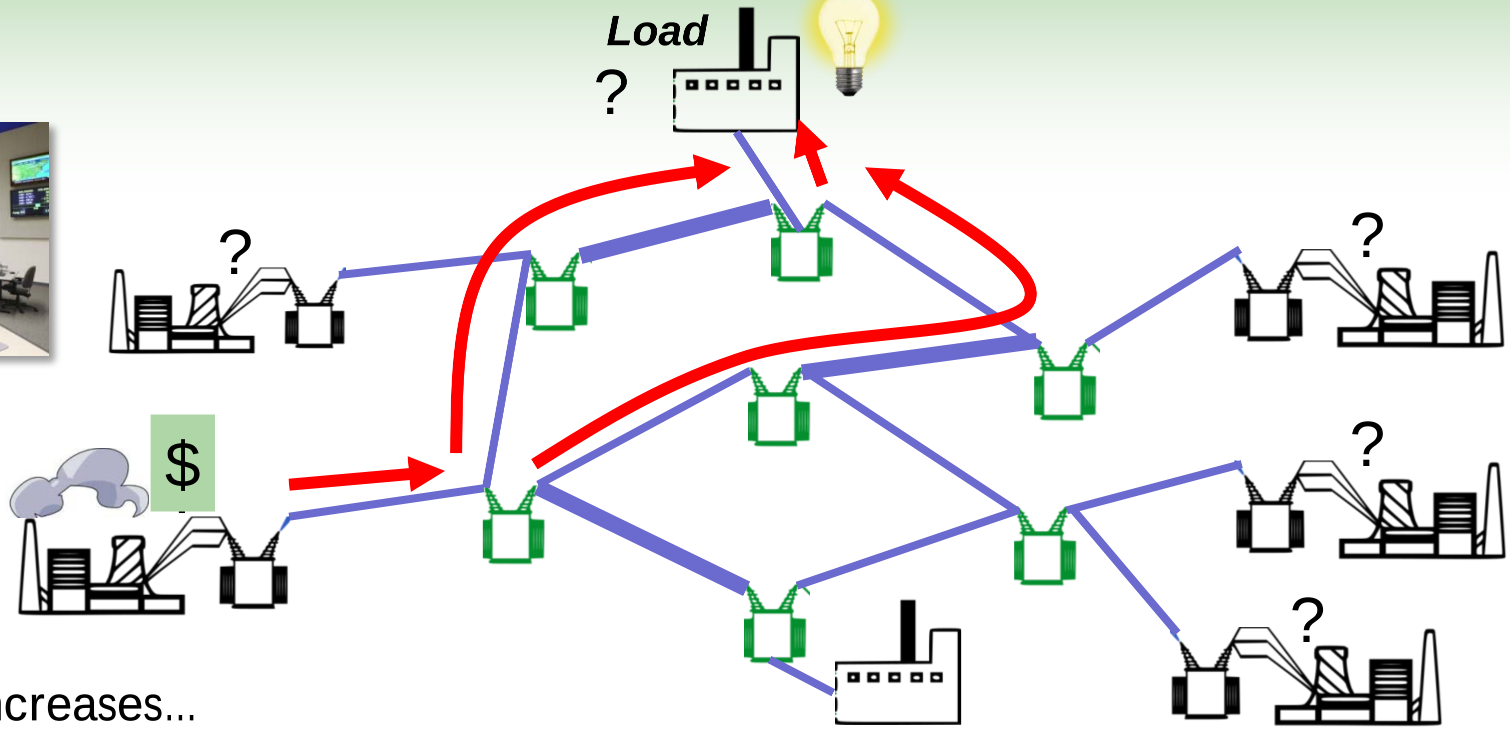
- $354 B electricity sales
- 166,000 miles operated by 500 companies

  98% AC, voltages > 100kV
- 3 major interconnections
- 3,170 utility companies
- Over 140 control areas

- 14,000 transmission substations
- ~44 million liquid-immersed distribution transformers in service in 1995
- ~12 million dry transformers

Sources: 1996 ORNL, "Determination Analysis of Energy Conservation Standards for Distribution Transformers"; and DoE Office of Electricity Delivery and Energy Reliability

Delivering Electricity



As demand increases…

…day-ahead market & spot market coordinate additional generation

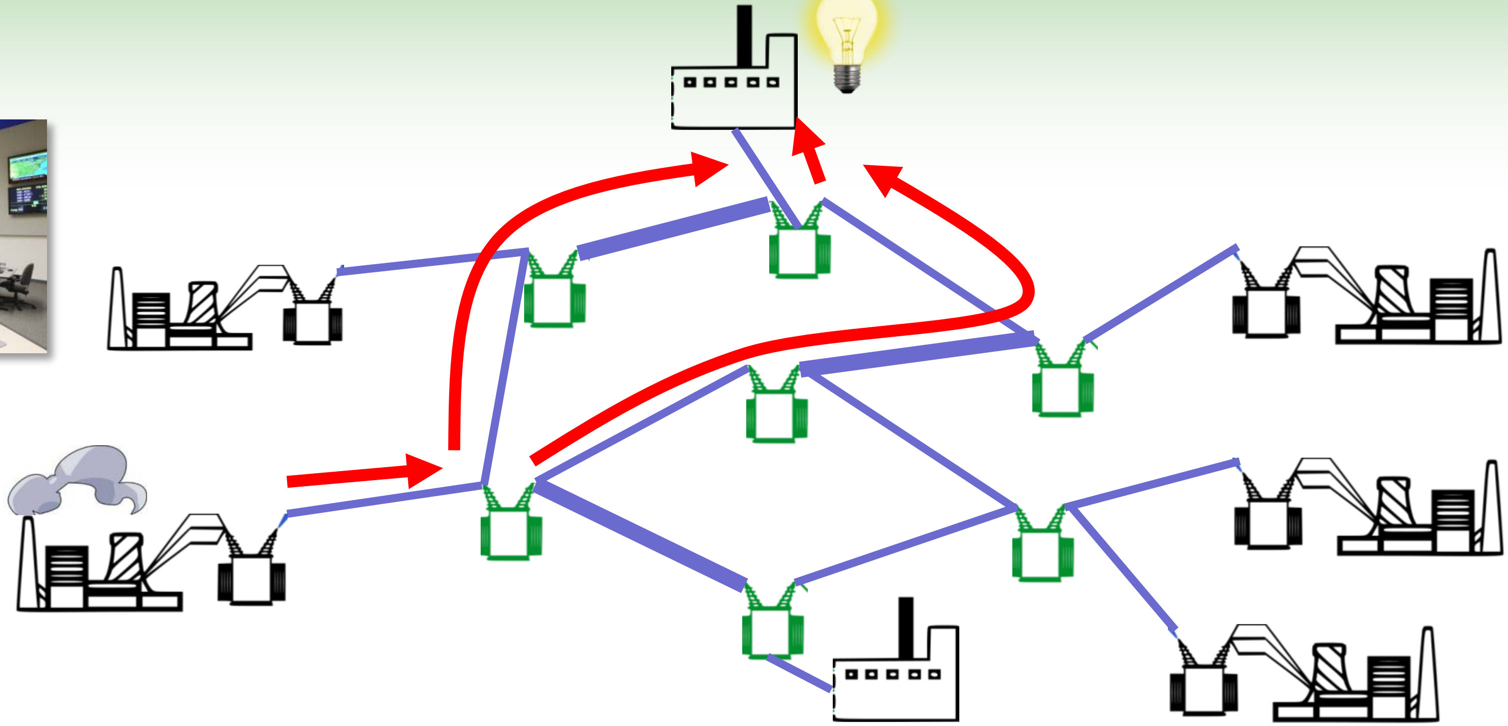
…generator spins up: coal/nuclear /gas (day-ahead), gas (spot market)

…power flows into the grid

…electrons flow along path of least resistance

…the load draws power from the grid

Delivering Electricity



- Negligible storage – just in time delivery of power
- Centrally controlled
- Negligible control of path – Joules are indistinguishable

Not the internet

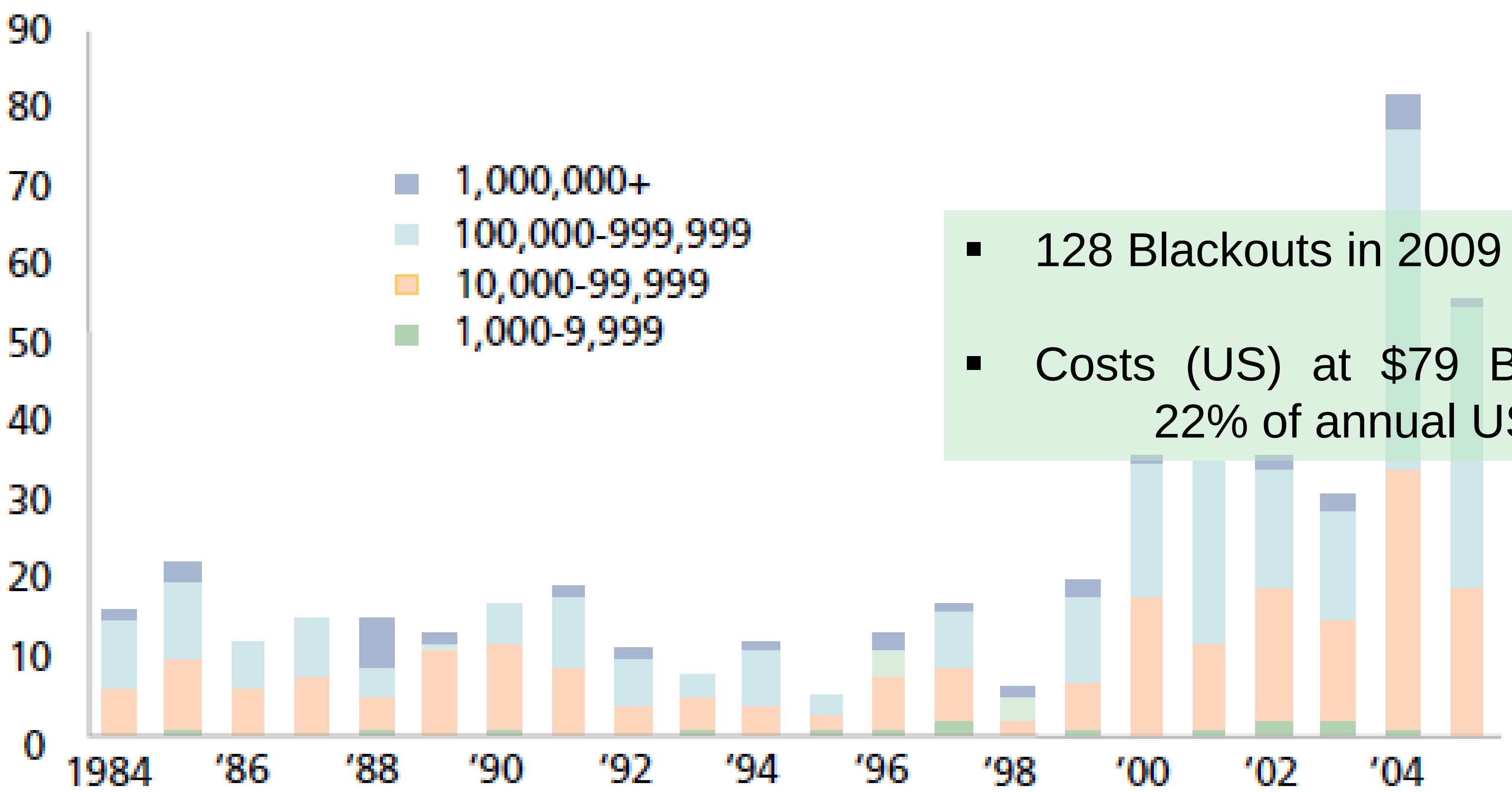
Drivers for Change

ARPA-E Workshop

The White Space

Increasingly Unreliable

Blackouts measured in customers affected



- 128 Blackouts in 2009
- Costs (US) at $79 Billion annually – 22% of annual US electricity sales

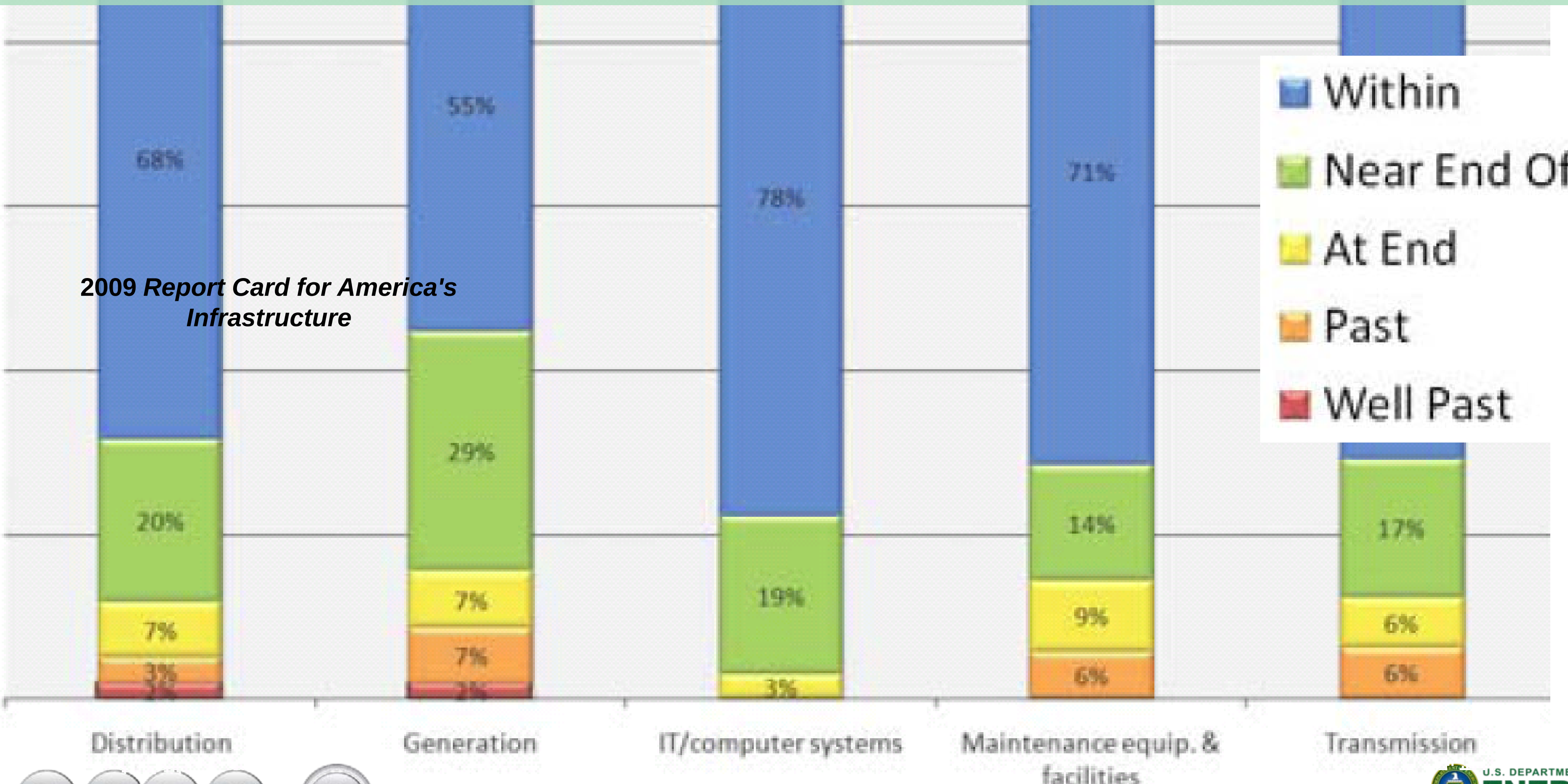
Source: NERC DAWG records and EIA data cited in Hines, Apt, Liao, Talukdar

Aging Infrastructure

"average generating station was built in the 1960s using even older technology.

"average age of a substation transformer is 42, 2 years more than…life span."

Source: Galvin Electricity Initiative

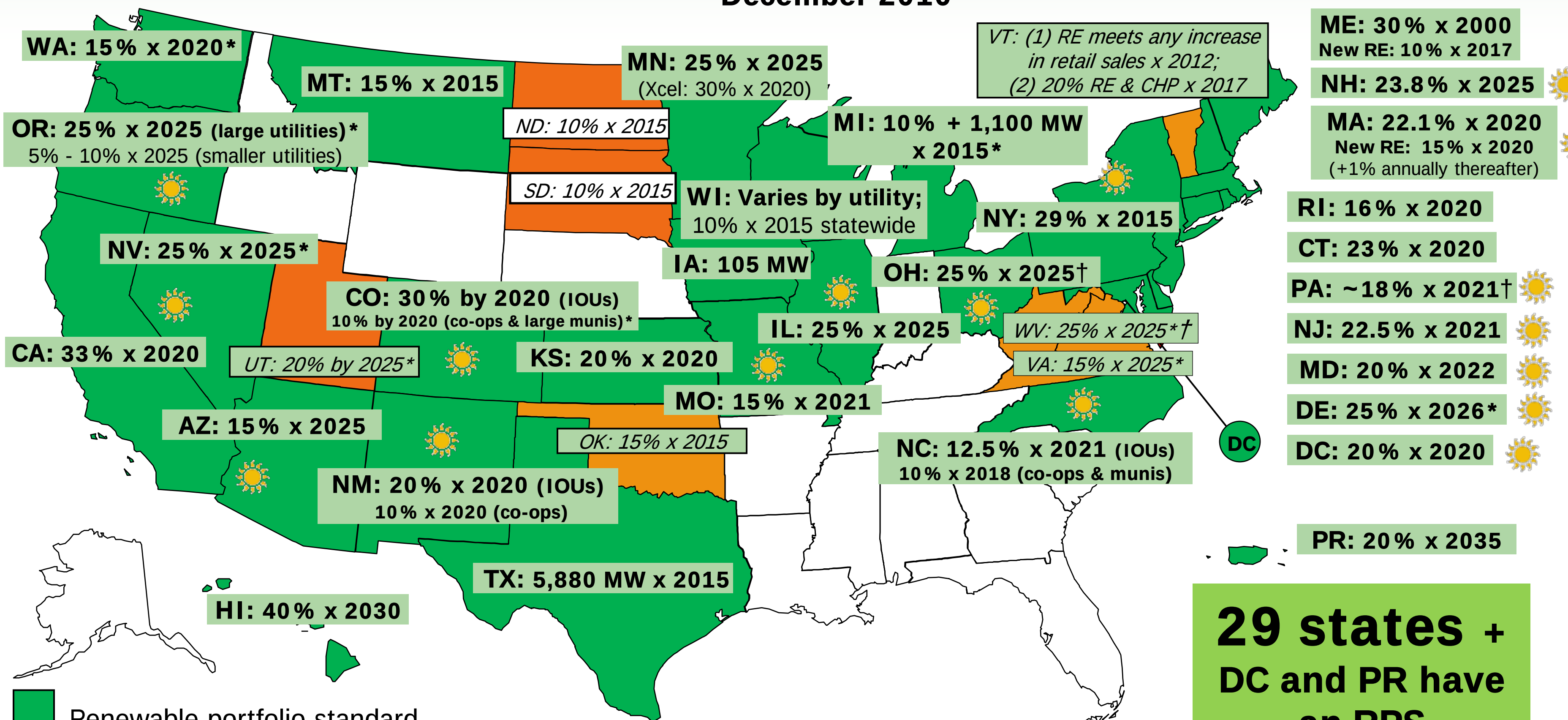


2009 ***Report Card for America's Infrastructure***

Increasingly Unpredictable

Proliferation of non-dispatchable generation

December 2010



Renewable portfolio standard

Renewable portfolio goal

Minimum solar or customer-sited requirement

* Extra credit for solar or customer-sited renewables

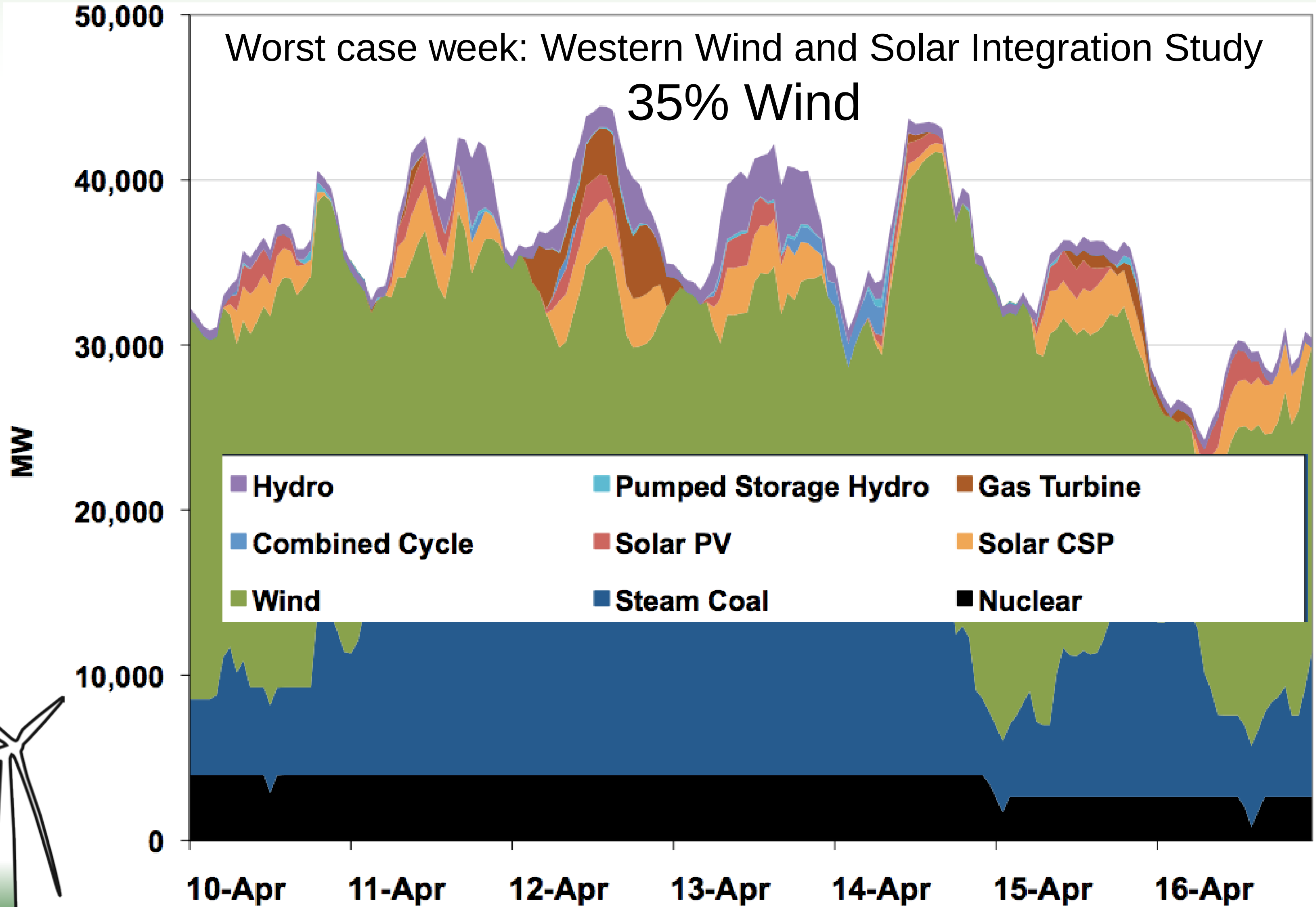
† Includes non-renewable alternative resources

29 states + DC and PR have an RPS

(7 states have goals)

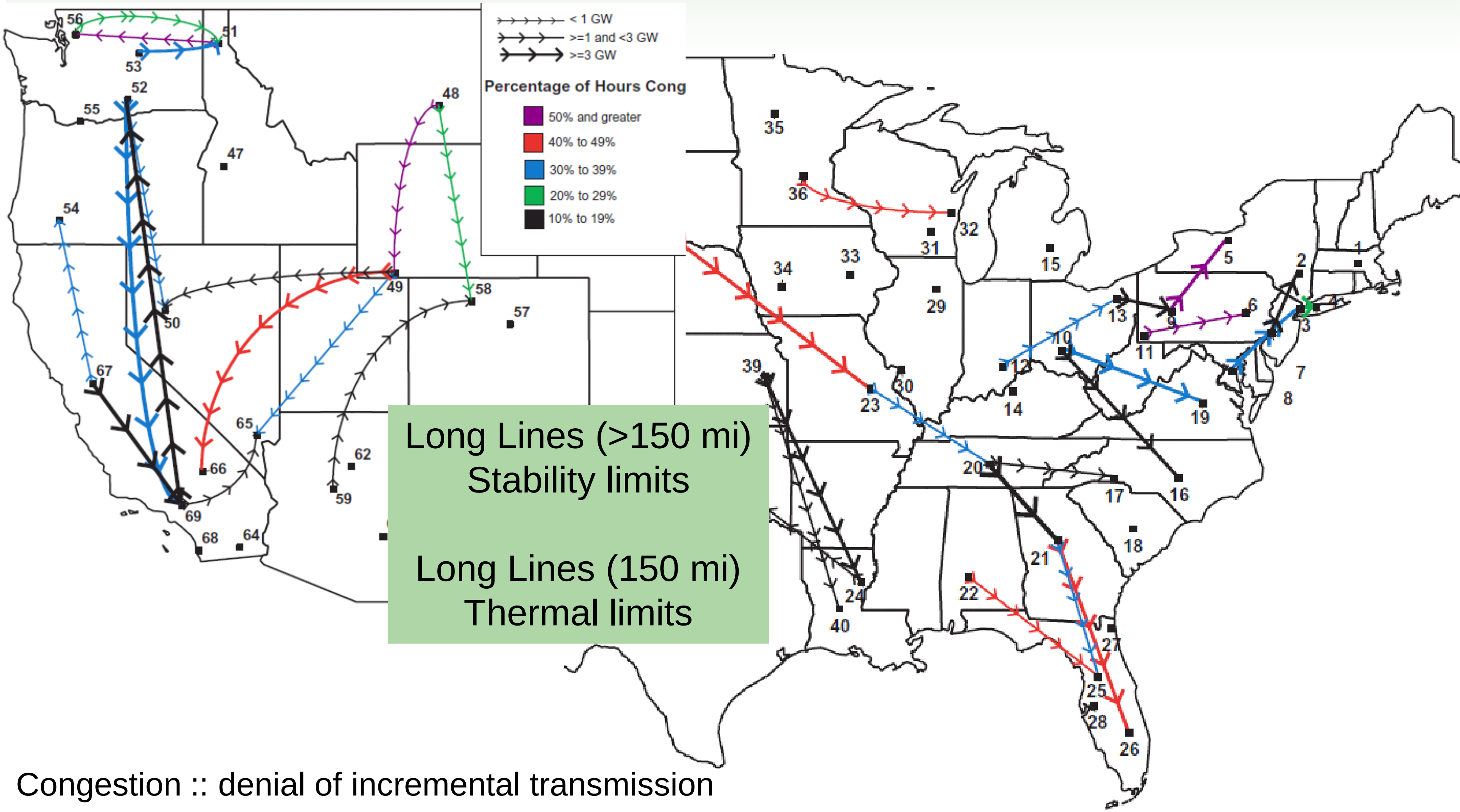
www.dsireusa.org

Increasingly Unpredictable



Source: Debra Lew, 2010 Western Wind and Solar Integration Study

Congested Lines



Long Lines (>150 mi)
Stability limits

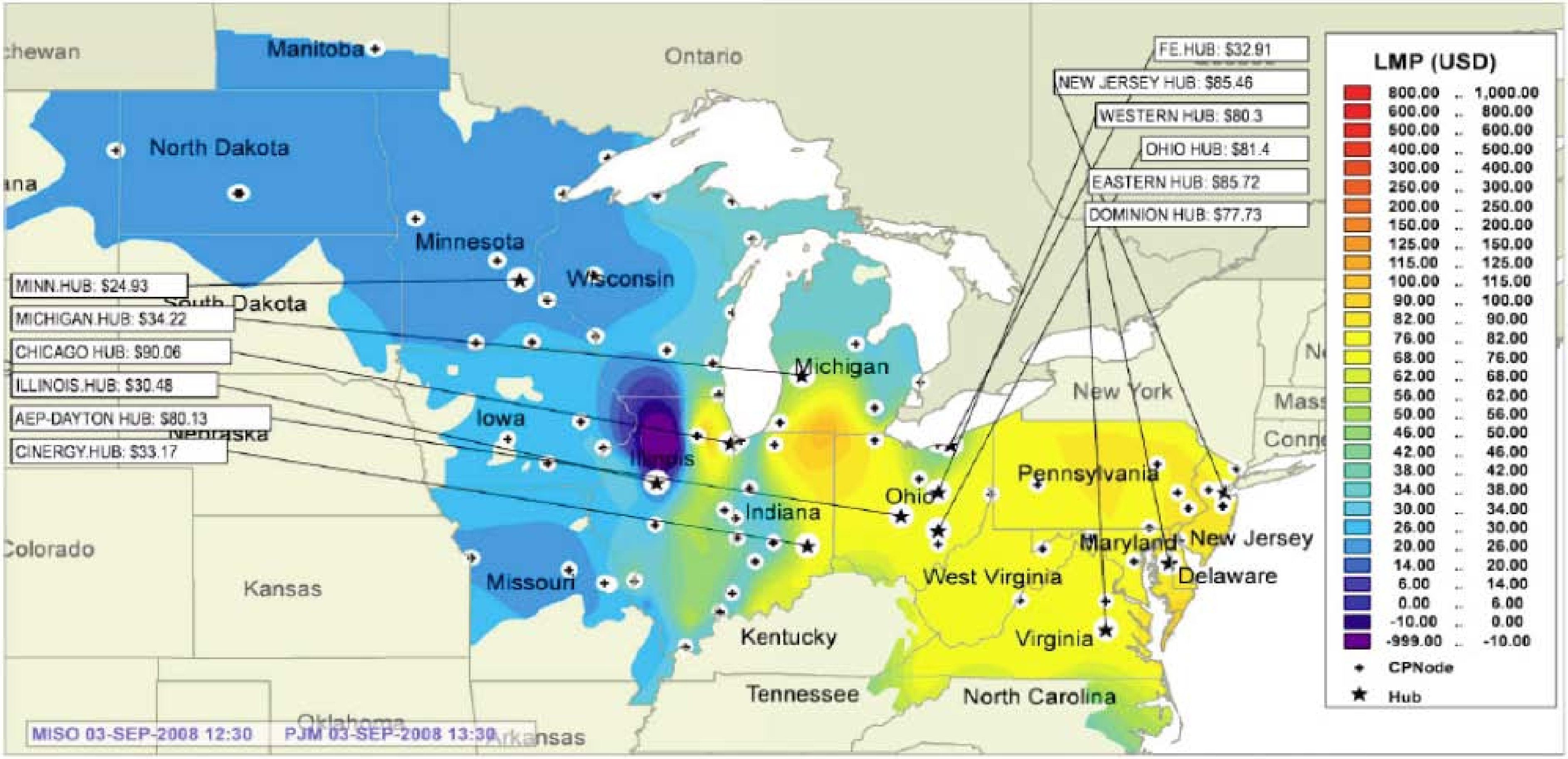
Long Lines (150 mi)
Thermal limits

Congestion :: denial of incremental transmission

Source: May 2002 DoE National Transmission Grid Study

Inefficient Markets

Location marginal pricing



This image will be refreshed in **3** Minutes, **4** Seconds. Please hit crtl-F5 to manually refresh this page.

Drivers for Change

ARPA-E Workshop

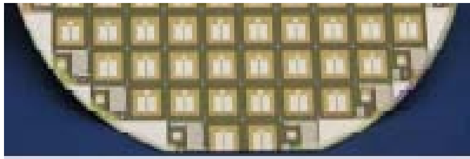
The White Space

How do we make a more flexible, controllable electricity grid?

Workshop Overview

Academia (power systems)
4 participants
Presentation: Deepak Divan, GTech
"Dynamic control of grid assets"

Academia (control)
12 participants
Presentation: Munther Dahleh, MIT
"Network control"

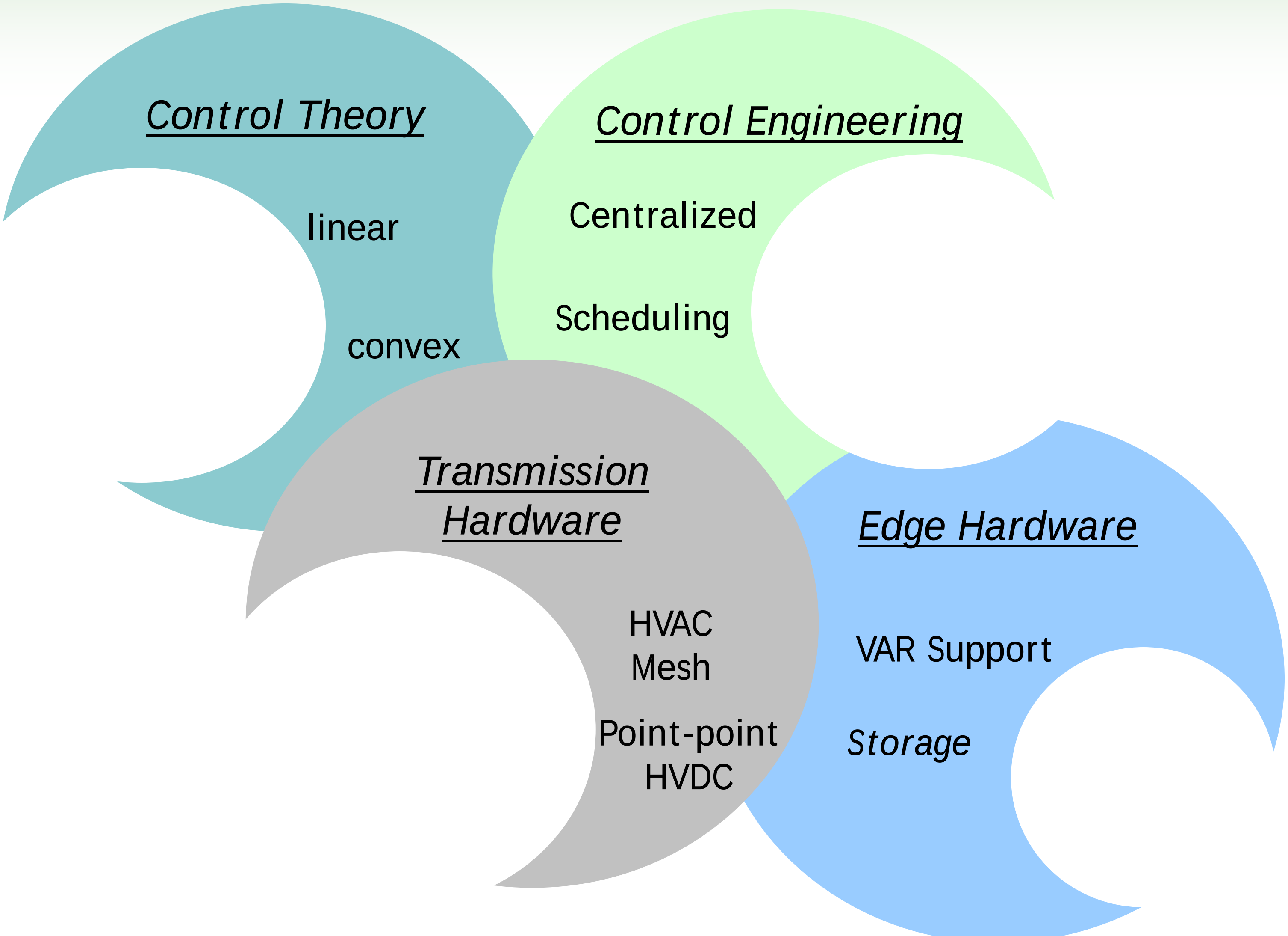


Government
18 participants (10 from national labs, 5 DOE, NSF, NIST)
Presentation: Debra Lew, Senior Project Lead NREL
"Western Wind and Solar Integration Study"

Utility/RTO
7 participants
Presentation: Terry Oliver, CTO BPA
"Integrating Renewable Resources into the Electric Grid"

Vendors
9 participants
Presentation: Le Tang, CTO ABB
"Future Transmission, HVDC &FACTS"

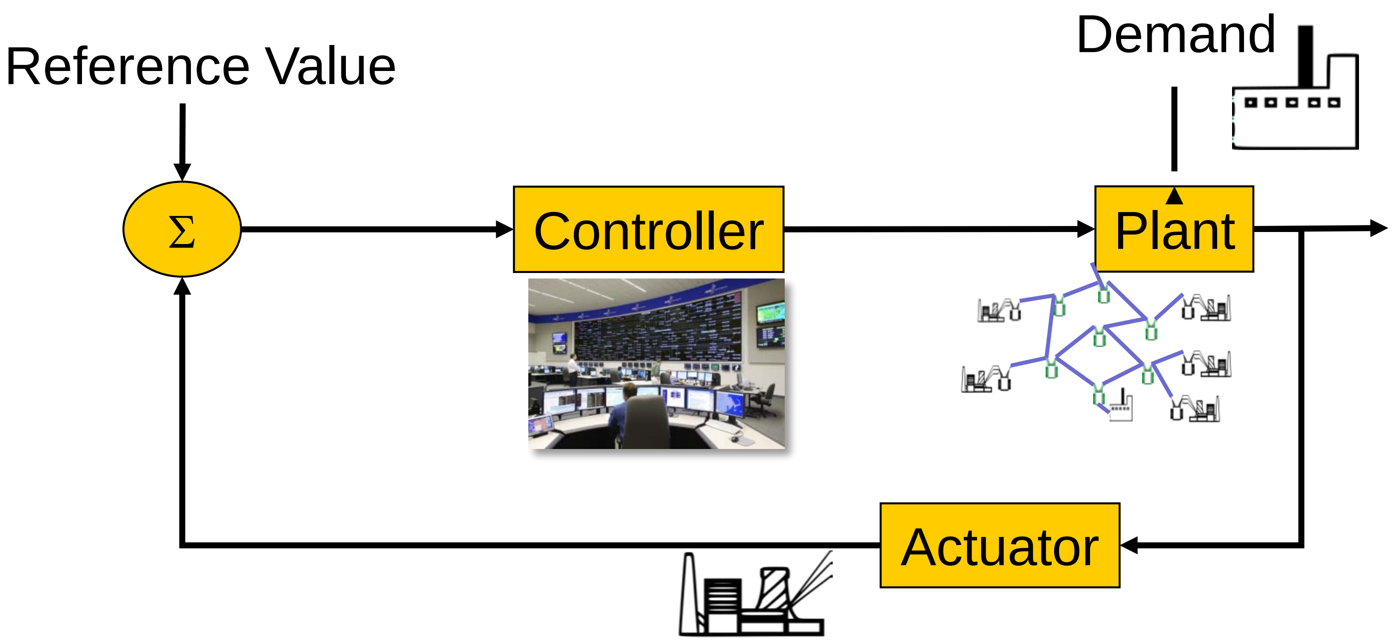
Workshop Findings



Control Theory

Objective:

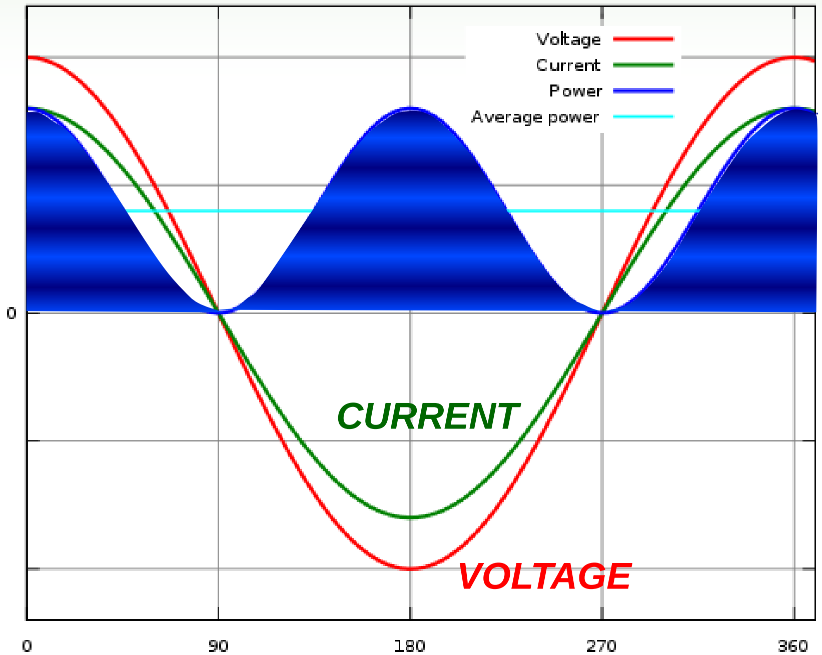
- Generated Power = Power into Load
- Reliability, Cost, Frequency Control, Voltage Level, etc



Control = Sensing + Computation + Actuation

Control Variables

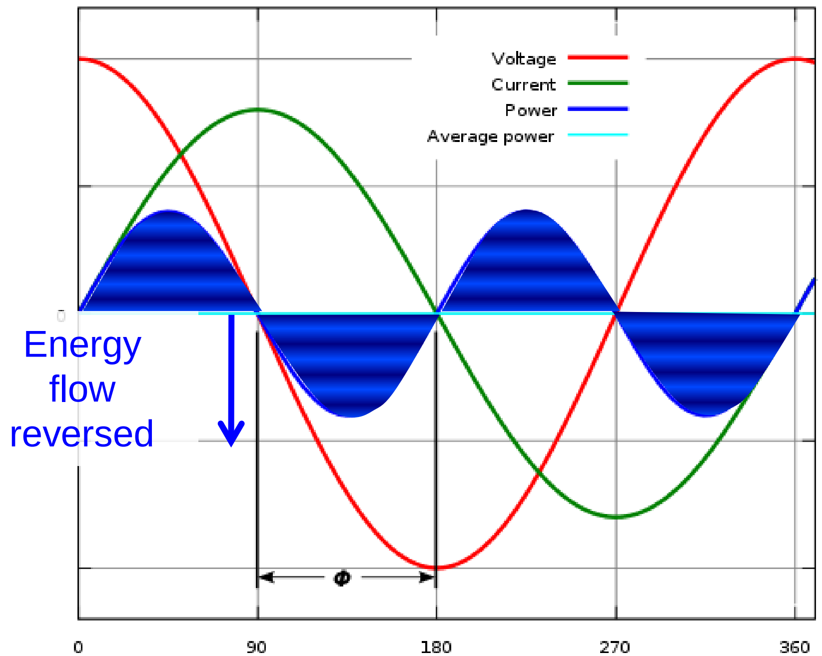
REAL POWER



time

$$P = IV \quad Power = Current \cdot Voltage$$

REACTIVE POWER



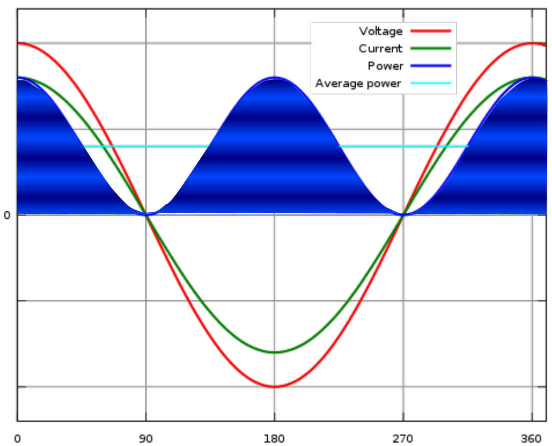
time

Voltage Waveform & Current Waveform

or

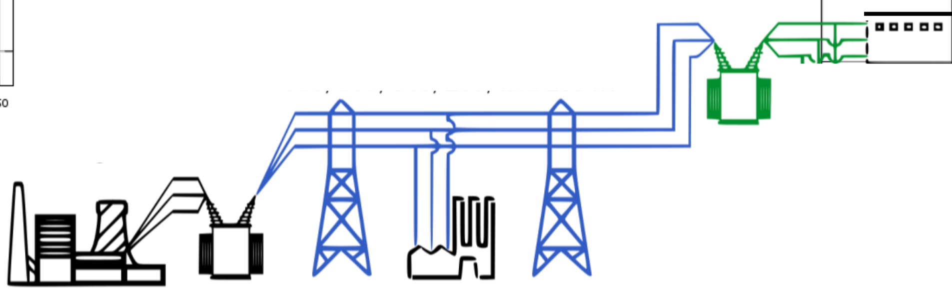
Real Power & Reactive Power

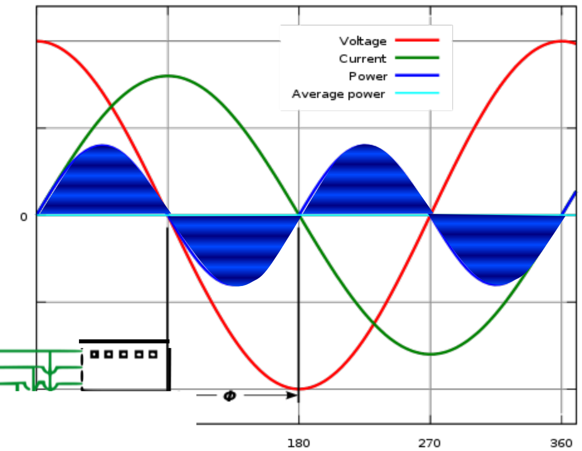
Real and Reactive Power Conversion



I = Y V

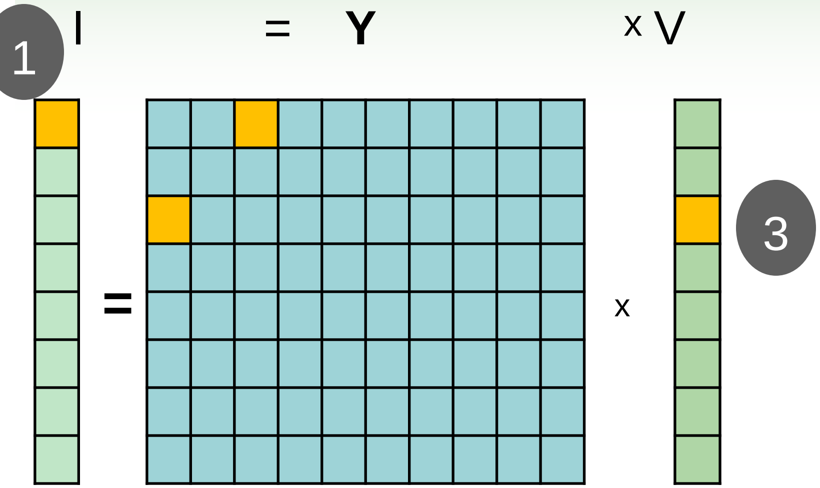
Y (inductance of line)
sets change in phase

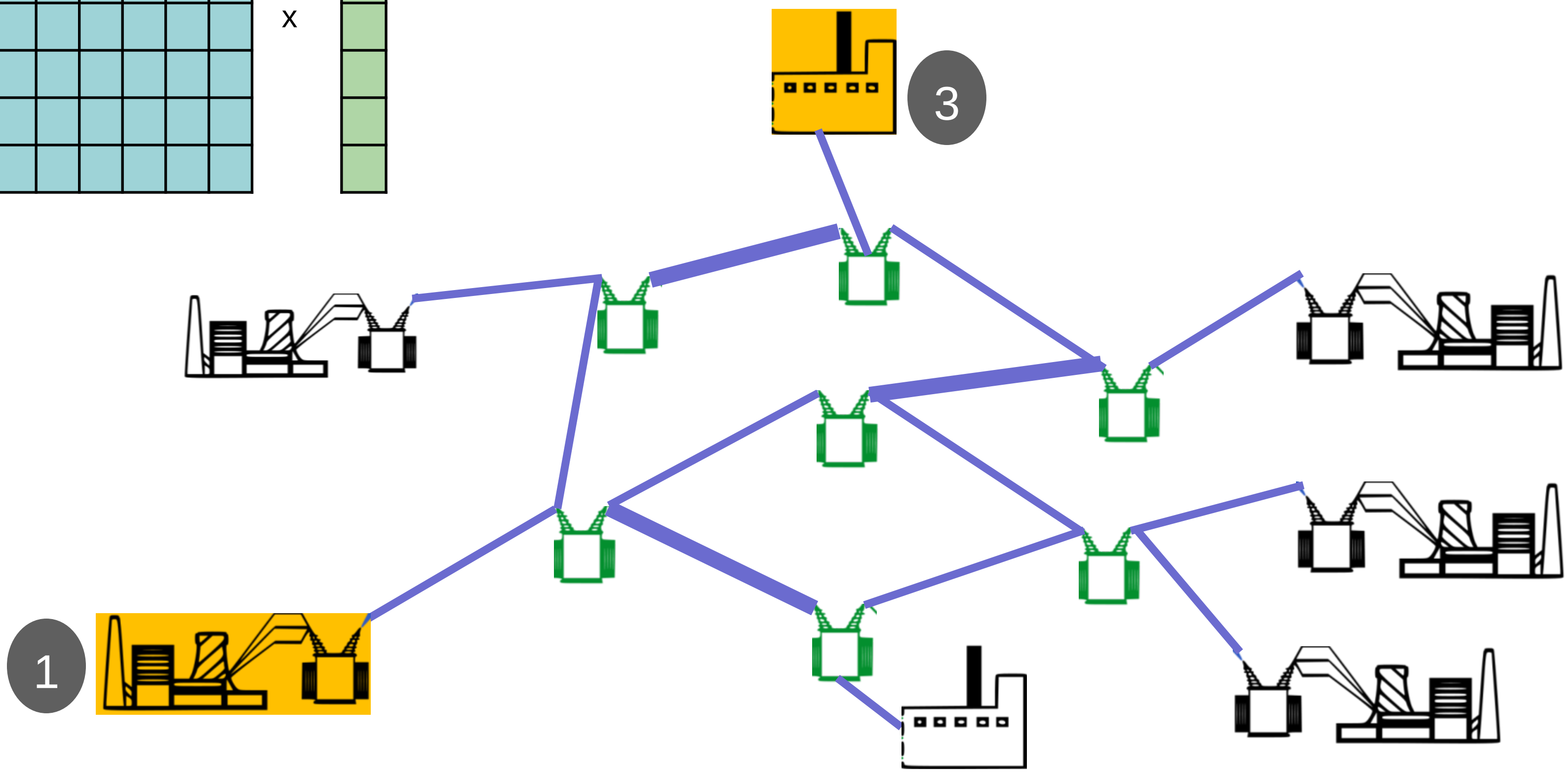




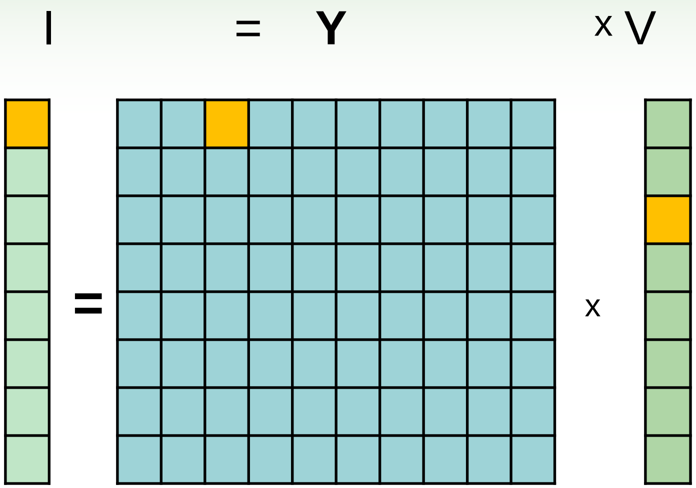
Designing Power Flow

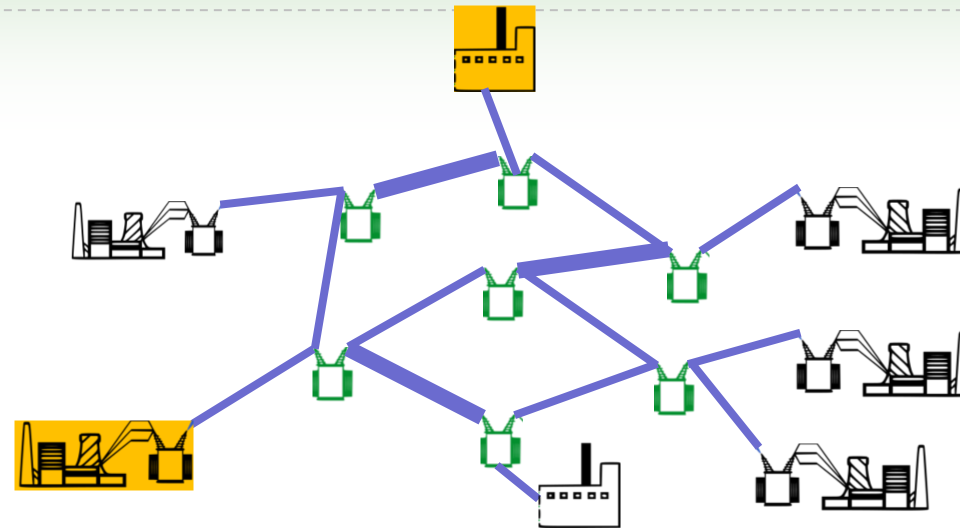
$I = Y \times V$





Controlling Power Flow





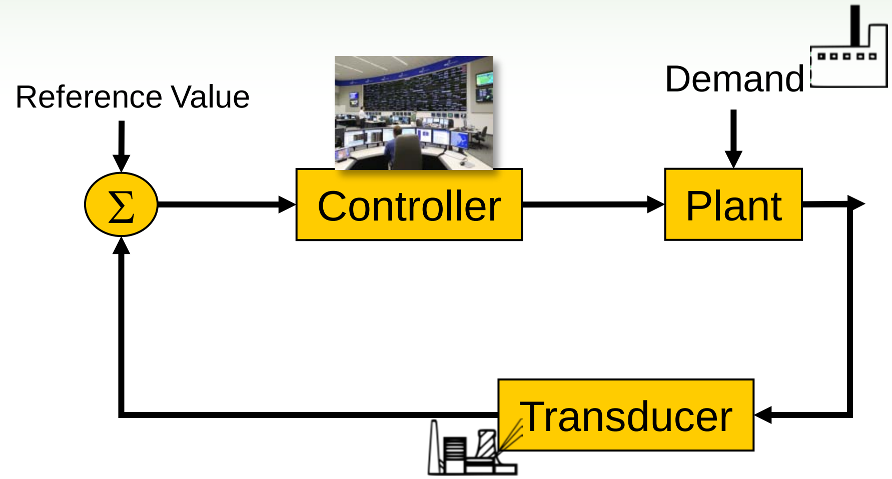
Minimizing the cost of fuel to deliver power is Hard (NP)

Must search through many choices of generator outputs for achieving a desired load

What kind of control?

- Linear vs. Non-linear
- Deterministic vs. Stochastic
- Time-invariant vs. Time-varying
- Continuous-time vs. Discrete-time

Controlling Power Flow



Power Flow Control

- Feed-forward control
- Assume:
  - Linear
  - Deterministic
  - Time Invariant

- Central control

Error (Frequency, Voltage)

- Feedback control
- Account for
  - Non-linearity
  - Dynamics

- Distributed or local control

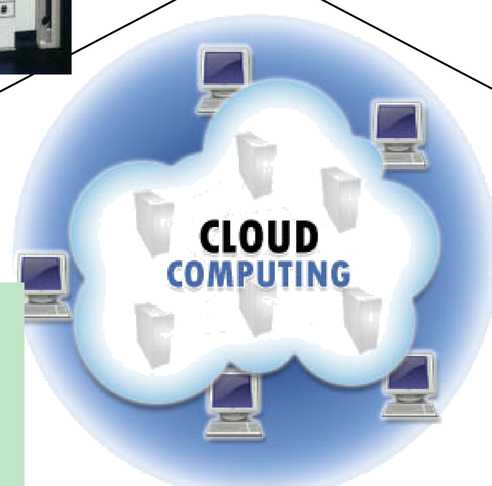
Control Infrastructure

Improved Sensing

A PMU measures
- Current (Hall sensor)
- Frequency (LC Circuit)
- Time (GPS)
- Voltage
- Relative Phase
- **Sample 30 msec**

Improved Communications

Grid Connected Router
- Low-latency
- MPLS
- Cyber security
- 100-600 μs For crypto



Distributed computing
- Fast
- Secure
- Resilient

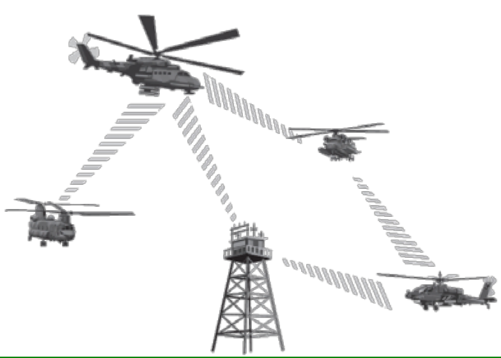
Improved Computation

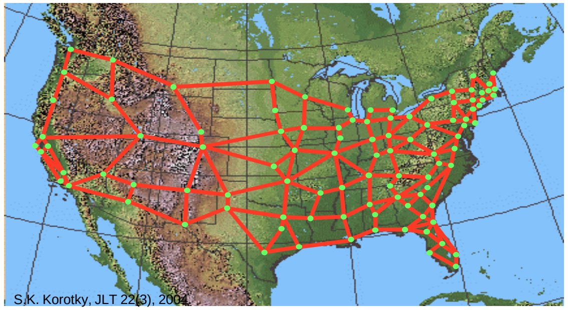
Control Challenges

- Traditional control theory assumes centralized feedback control.
- Not always feasible for large-scale distributed systems:
  - Inability to communicate with all subsystems
  - Incomplete/imperfect information
  - Complexity of centralized decision-making
  - Asynchrony
  - Heterogonous decision-makers with different objective and uncertain responses

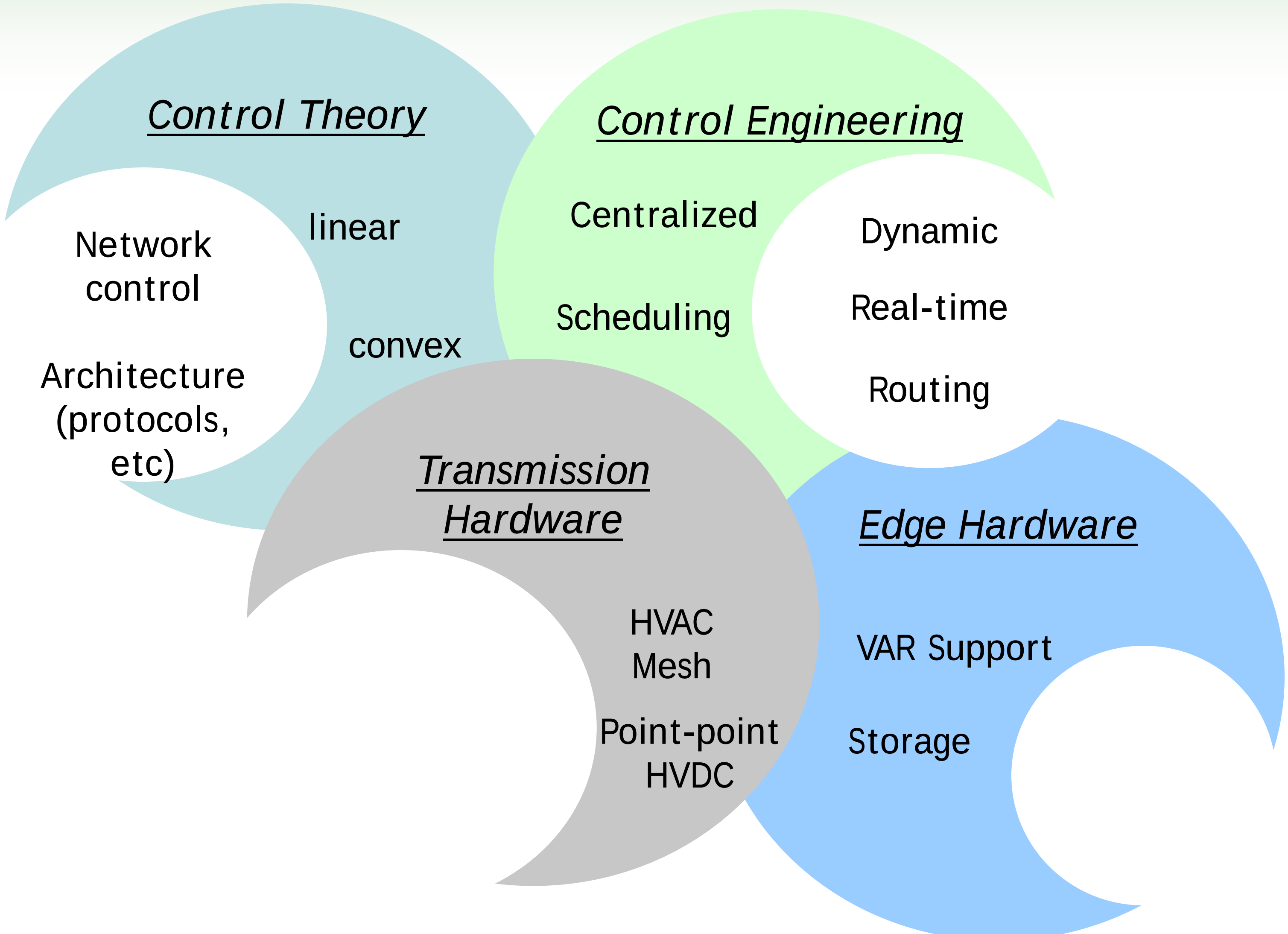
Networked control **(Developed since 2005)**

- Several layers: Physical, communication, and decision network
  - The physical layer consists of several distributed subsystems, coupled through and/or economics, via static and/or dynamic constraints.

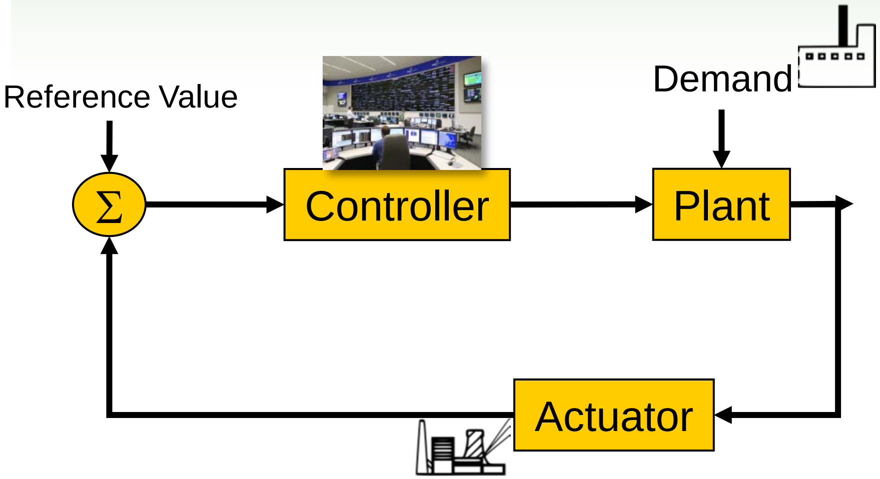




Workshop Findings



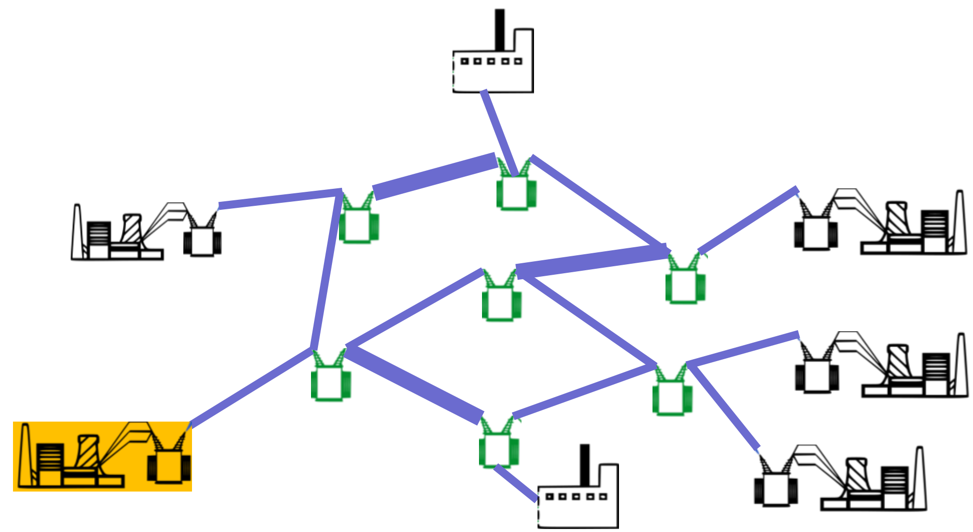
Actuators



Demand Response

Schedule demand

(eg. large industrial loads)



Control in the Grid

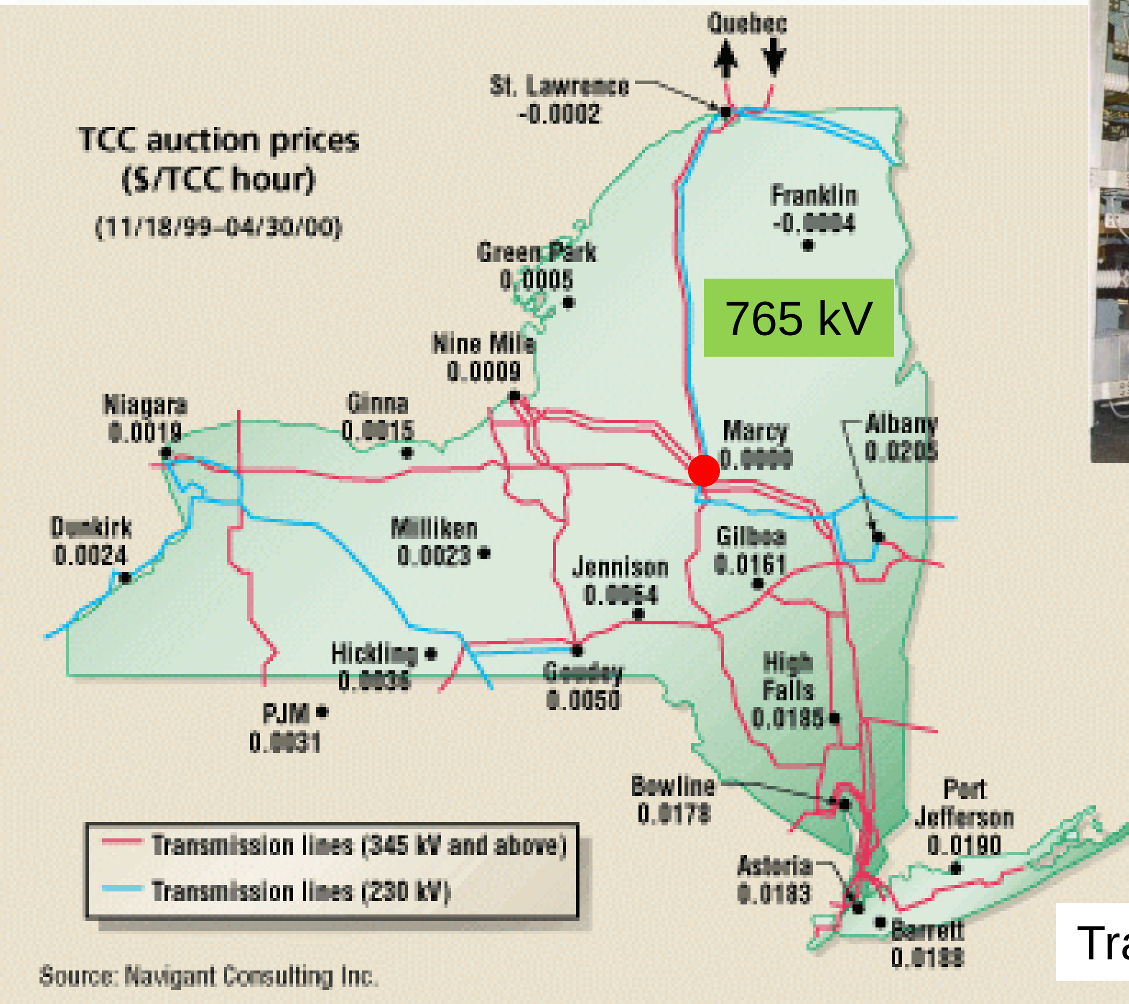
Flexible AC Transmission System:

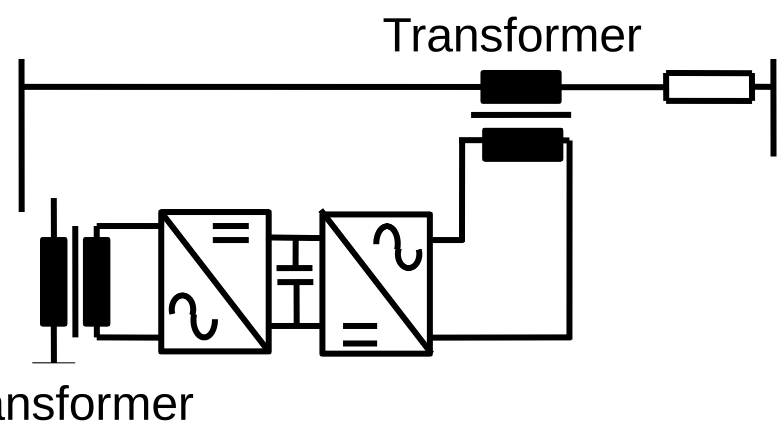
- Static VAR
- STATCOM
- UPFC

Power Flow Controller (AC)

AC Univesal Power Flow Controller

Global Total = 3   Cost=$140/W

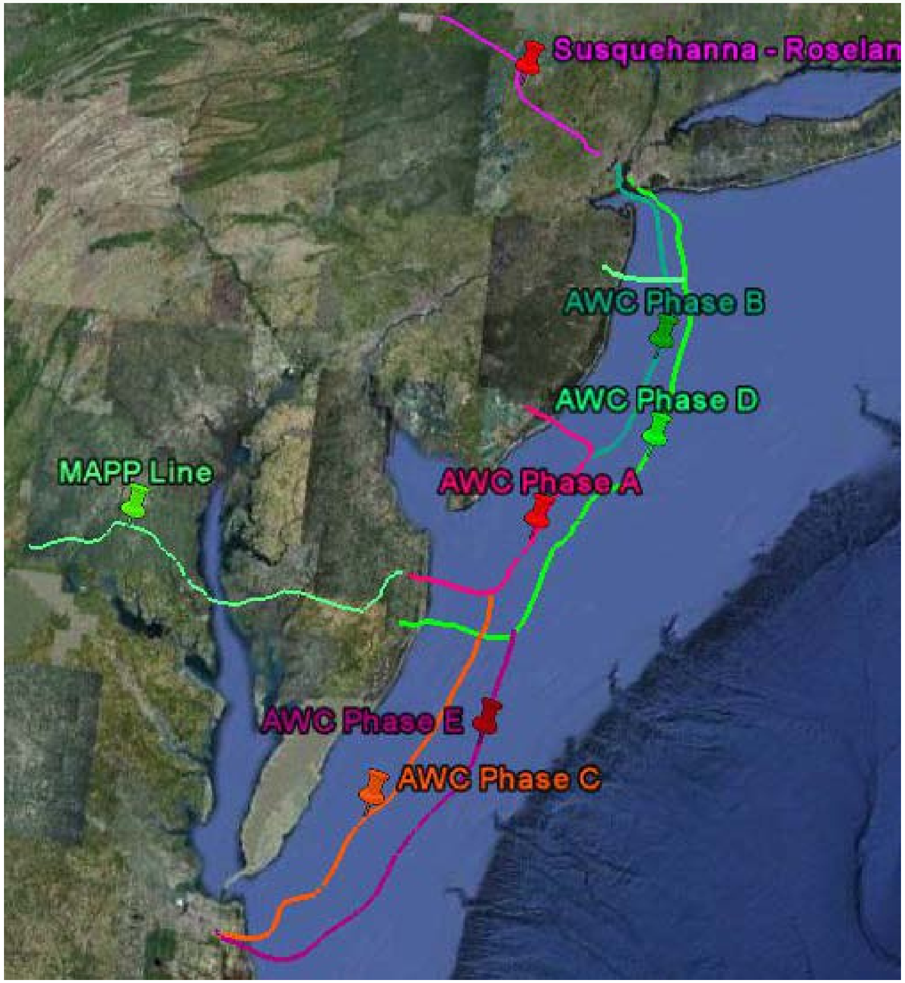




Power Flow Controller (DC)

Multiterminal HVDC

Cost=$900/W Line=$1M/MW.mi Term=$250k/MW



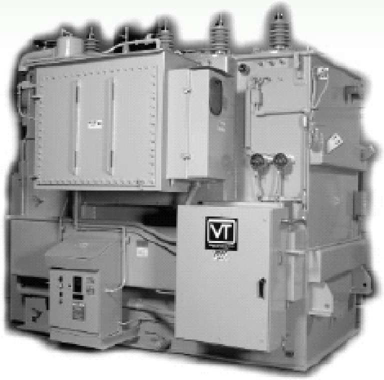
- $5.2 B (5 phases)
- Offshore multi-terminal voltage-sourced converter (VSCs) backbone
- 6000 MWs of offshore wind farms in federal waters off of NJ, DE, MD & VA
- PJM Total Peak Load = 144,644 MW
- Funded by Google, Good Energy & Marubeni Power
- Optimal power flow scheduling over 2000-MW transfer capability
- Adds 2 independent transmission circuits

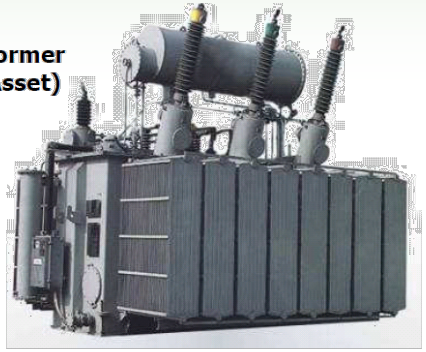
  into PJM
- First phase energization: 2016

Source: Mohamed M. El-Gasseir, Atlantic Wind Connection

NEXT GENERATION HARDWARE

Power Converter Augmented Transformers





LTC Transformer (Grid Asset)

LTC Transformers

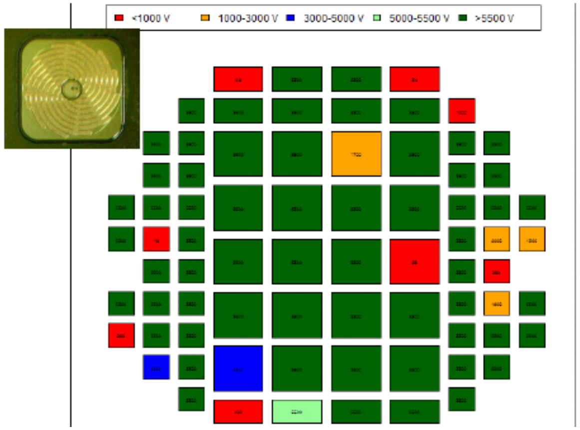
Dispatchable P/Q

ARPA-E Funded

- Refit existing transformers
- A fail-normal mode
- Fractionally rated converters

Resilient HVDC

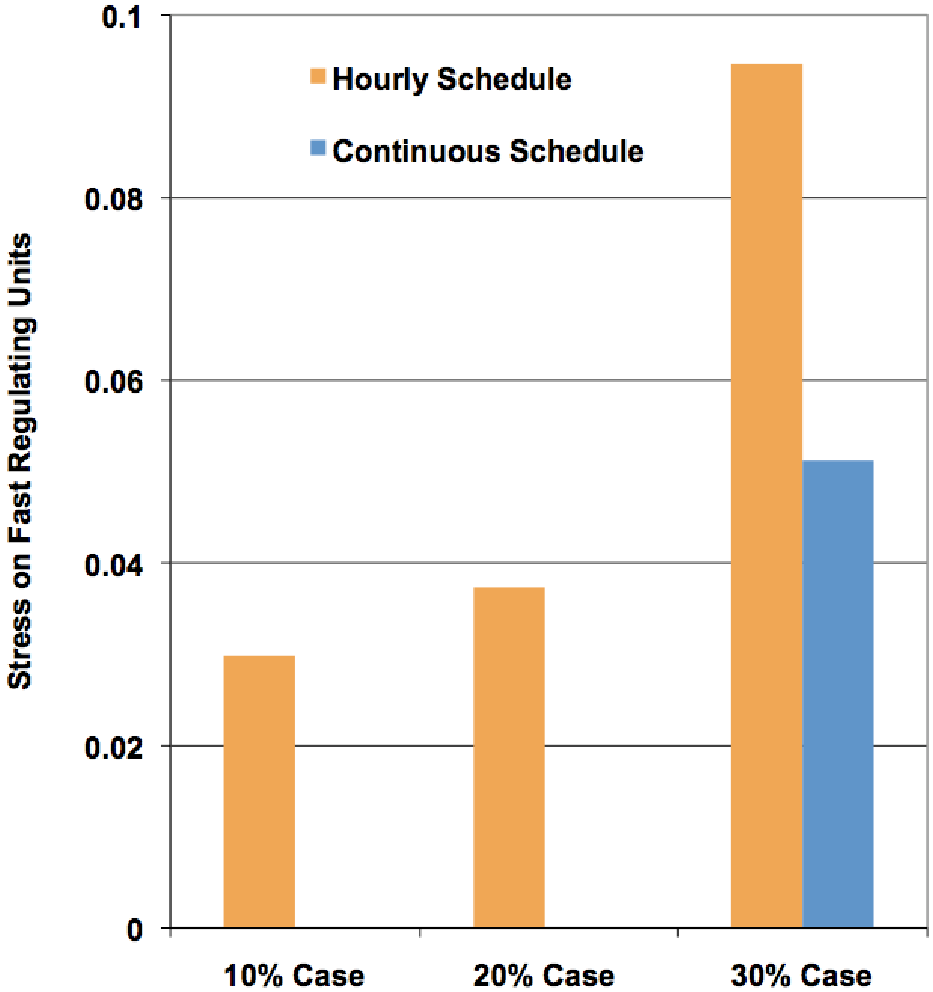
15kV limiter
6kV Si GTO

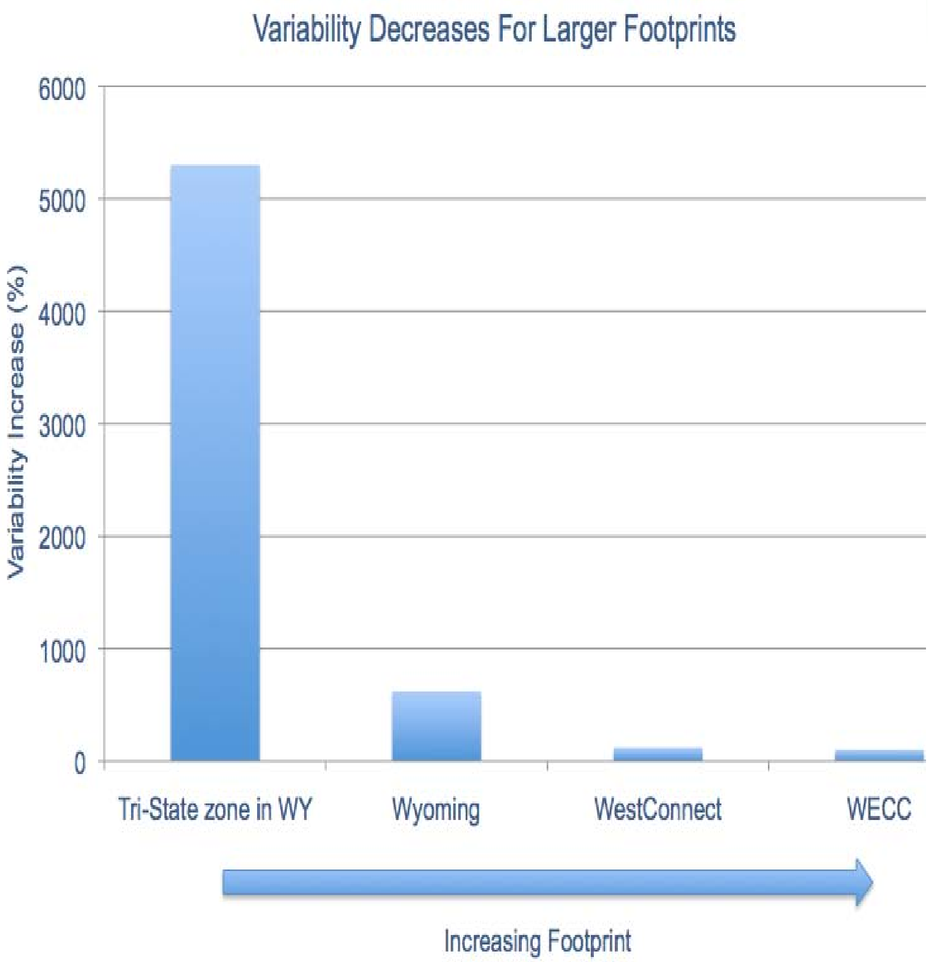


- HVDC fault protection
- High capacity, low cost cable
- High-voltage, uncooled

ADEPT Goal: 13kV SiC GTO

Managing Non-dispatchable Generation





Source: Debra Lew, 2010 Western Wind and Solar Integration Study

Drivers for Change

ARPA-E Workshop

The White Space

Missing Control Architecture

Major Trends

- Moving to real-time, closed loop control over wide-area
- More controllable AC grid
- Multi-terminal HVDC for improved transport

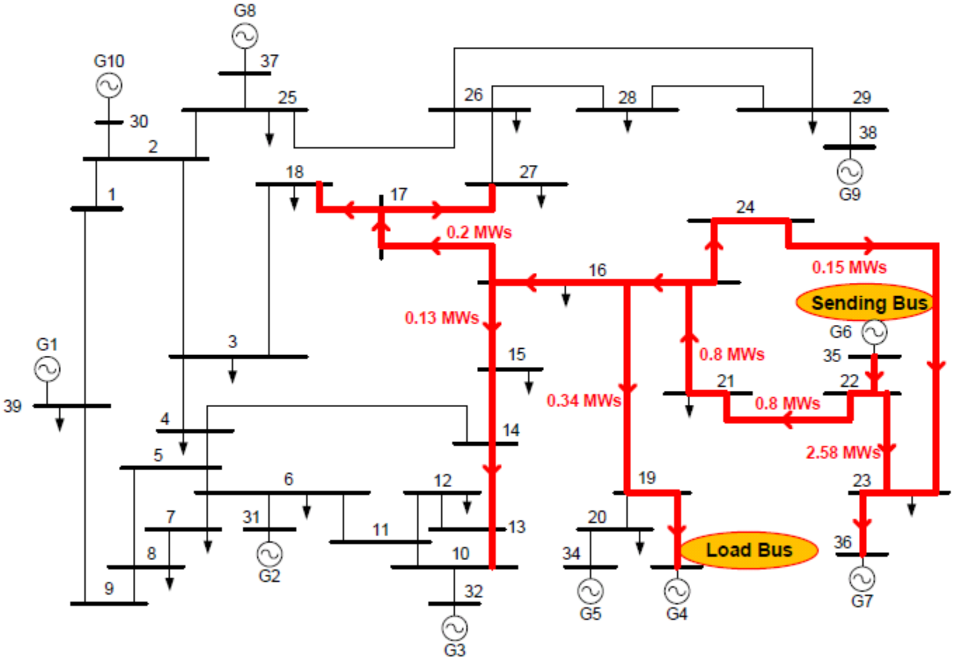
Future

- Need a comprehensive architecture for control & actuation
- Need a path for incremental technology adoption

Benefits of Routing Power

Today: Uncontrolled Flows

Power Routing



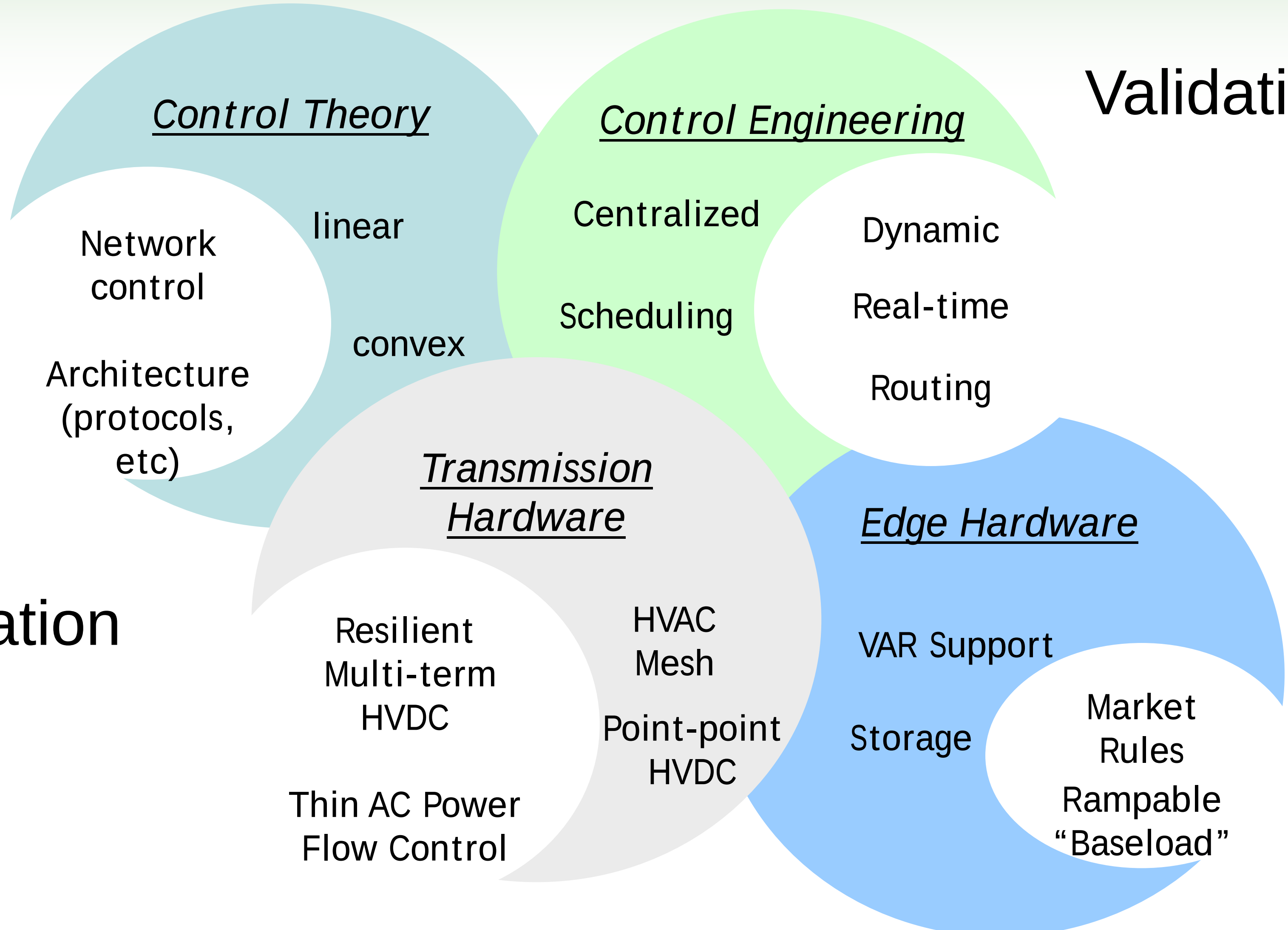
Base Case: 3.4 MW sent; 0.34 MW recd

•Power flow control to route power along underutilized paths, 80% less transmission infrastructure required

GA Tech study of simplified IEEE 39 Bus system with 4 control areas, operation simulated for 20 years, 20% RPS phased in over 20 years, sufficient transmission capacity added each year to eliminate curtailment of renewable generation

GENI

Validation



Validation